Large effective area non-zero dispersion shifted fiber in metro/provincial network environments

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ABSTRACT

In this paper, we experimentally study the performance of a large effective area non-zero dispersion shifted fiber over distances characteristic of metropolitan and provincial area networks, with a wide variety of commonly used transmitter types. The experiments are performed without dispersion compensation to simulate current network designs. The transmitters tested include externally modulated lasers, directly modulated lasers, lasers with integrated electro-absorption modulators, bit rates of 10 Gb/s and 2.5 Gb/s, and wavelengths from 1310 nm to 1610 nm. We find that the non-zero dispersion shifted fiber compares favorably with standard single mode fiber for many transmitters, offering reach advantages of 3-4 times in the 1550 nm band. Deployment of such a low dispersion fiber in metro/provincial networks may allow the use of some transmitters currently not practical, such as 10 Gb/s directly modulated lasers in the S-, C-, and L-bands. In general, it provides comparable or superior performance with today's current transmitters, and allows the possibility for future upgrades to higher bit rates and longer link lengths that may not be feasible with standard single mode fiber.

Keywords: Metro networks, dispersion, non-zero dispersion shifted fiber, large effective area fiber.

1. INTRODUCTION

To date, non-zero dispersion shifted fiber (NZ-DSF) has been primarily deployed in long-haul networks for high bit rate applications, while fiber deployments in metro and provincial area networks have predominantly been standard single mode fiber. However, the fiber requirements of metro/provincial networks are now starting to approach those of long-haul networks in some ways as higher bit rates and DWDM systems are deployed. Moreover, transmission distances in metro networks are lengthening as metro and provincial or regional networks start to merge together. Both the increasing bit rates and longer distances prompt interest in the use of NZ-DSFs in such metro/provincial networks. In this work, we experimentally demonstrate the flexibility of a large effective area NZ-DSF for metro/provincial networks. The fiber's low chromatic dispersion at 1550 nm and large effective area are shown to work well with several different laser sources and bit rates, and to offer significant reach advantages over standard single mode fiber in many cases.

Metro/provincial networks are characterized by transmission distances up to about 300 km, and the use of a wide variety of bit rates, transmitter types, and laser wavelengths. For example, inexpensive transmitters such as directly modulated lasers (DMLs) and integrated electroabsorption modulated lasers (EMLs) are commonly found in these networks but not in the long-haul space because of deleterious chirp effects. Dispersion effects usually limit 1550 nm transmission distances in metro/provincial networks, however, the use of dispersion compensation is often avoided. While standard single mode fiber remains the primary fiber deployed in most networks, its high dispersion of approximately +17 ps/nm/km in the 1550 nm region limits transmission distances to 80-100 km for many transmitters, and the reach can be much shorter for some transmitters such as directly modulated 10 Gb/s lasers. We will show here that the low dispersion of the large effective area NZ-DSF at 1550 nm offers the ability to transmit over distances up 3 to 4 times as long as over standard single mode fiber in many cases.

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In this study we experimentally measure the transmission performance of Corning's large effective area NZ-DSF with an assortment of metro/provincial network transmitters and compare the performance and reach lengths achieved against those obtained with standard single mode fiber. Transmitters in the 1550 nm wavelength range that are measured include 10 Gb/s EMLs, 10 Gb/s DMLs, 10 Gb/s lasers externally modulated with a lithium niobate electro-optic modulator, and 2.5 Gb/s DMLs. In addition, we highlight its flexibility by showing 2.5 Gb/s transmission using directly modulated distributed feedback (DFB) lasers over a 50 km distance with a coarse wavelength division multiplexing (CWDM) system that spans a 300 nm wavelength range from 1310 nm to 1610 nm. The overall set of results suggests that the large effective area NZ-DSF, and/or a hybrid cable design incorporating both standard single mode fiber and the NZ-DSF, are well-suited for metro/provincial networks by offering the flexibility to accommodate a wide range of uncompensated link lengths, bit rates, and wavelengths and sources.

2. FIBER UNDER TEST

The fiber studied in this set of experiments is Corning Incorporated's LEAF® optical fiber. This fiber is widely deployed throughout the world, generally for high bit rate ($\geq$ 2.5 Gb/s) and long-haul network applications. It is a non-zero dispersion shifted fiber with nominal dispersion value at 1550 nm of 4.25 ps/nm/km, and it has a large effective area (~ 72 μm^2) at 1550 nm that can reduce the impact of optical non-linearities in comparison to other NZ-DSFs. It is compliant with ITU standard G.655 (all tables). The low dispersion has made it especially well-suited to transmission at 10 Gb/s and the large effective area allows the use of higher signal powers[1-4]. The zero dispersion wavelength is about 1500 nm. While this fiber is optimized for transmission applications in the erbium C- and L-bands, we will show here results that suggest capability throughout a broader spectrum down to 1310 nm, making it a versatile fiber for the metro and provincial network application space.

3. EXPERIMENTS AND RESULTS

The primary objective of this study was to evaluate LEAF® optical fiber in metropolitan and provincial network environments and to demonstrate its performance capabilities and advantages with the wide range of transmitter types that are typically used in these networks. The transmitters tested with the fiber included externally modulated lasers, integrated electro-absorption modulated lasers, directly modulated lasers, and bit rates of 10 Gb/s and 2.5 Gb/s. The transmitter wavelengths included the erbium C-band, and a CWDM system with wavelengths ranging from 1310 nm to 1610 nm. All measurements and experiments were conducted without dispersion compensation since designers of metro and provincial networks typically avoid the use of compensation elements.

3.1 Lithium Niobate external modulator

The first system studied was a 40 channel DWDM system with 100 GHz channel spacing, with the wavelength plan ranging from 1530 nm to 1562 nm. The lasers were modulated at 10 Gb/s with non-return to zero (NRZ) modulation format with an external lithium niobate electro-optic modulator. The full length of the system was 320 km, implemented with 4 spans of 80 kms each. The experimental set-up is illustrated schematically in Figure 1.

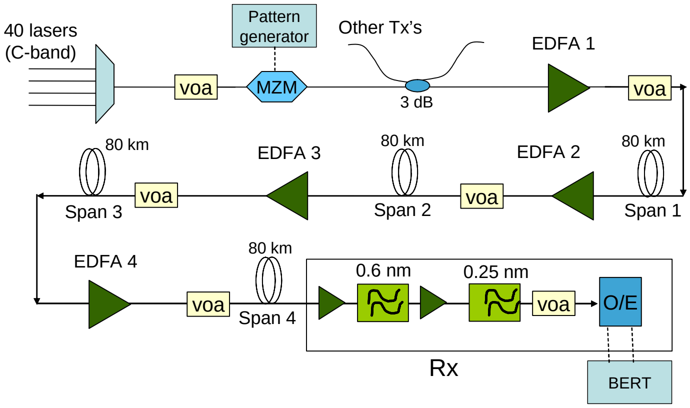


Figure 1: Schematic diagram of the experimental set-up used for 40 channel system with lithium niobate external modulator at 10 Gb/s.

The chirp of the lithium niobate modulator was nominally zero, and all channels were modulated simultaneously by the same device. Erbium doped fiber amplifiers (EDFAs) were used to compensate for the loss of the fiber spans (~ 16.5 dB per span including connectors) and to pre-amplify the signal before detection within the receiver. The average channel launch power into each fiber span was approximately 0 dBm. Tunable optical filters of bandwidth 0.6 nm and 0.25 nm were employed within the receiver to select a channel for detection and measurement. The pattern generator drove the modulator at 10 Gb/s with a pseudo-random bit sequence (PRBS) of length 2^{31}-1. The detector performed both optical-to-electrical (O/E) conversion as well as signal clock recovery, and the electrical signal and clock were output to the bit error rate tester (BERT) which was used to measure bit error rate (BER) and Q values.

The results of the Q values for 10 of the 40 channels transmitted through the system are shown in Figure 2. The 10 channels span the entire C-band, and are representative of the system performance across all wavelengths. The results are shown for various transmission distances up to the maximum of 320 km. Also shown are lines denoting Q values that correspond to BER = $1\text{x}10^{-15}$ (Q = 18 dB), and the threshold for error free transmission if standard forward error correction (FEC) is employed, which is approximately 11.5 dB.

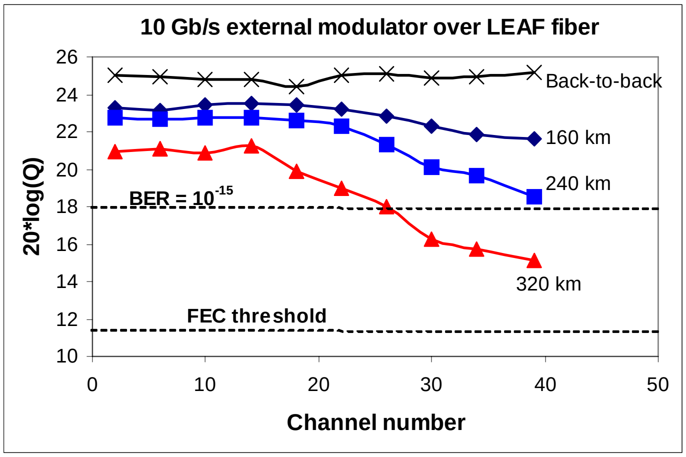
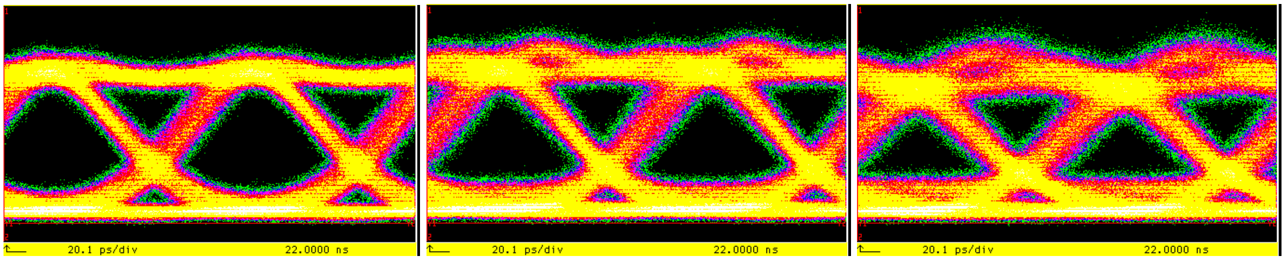


Figure 2: Results of signal Q values after transmission through up to 320 km of uncompensated LEAF® fiber.

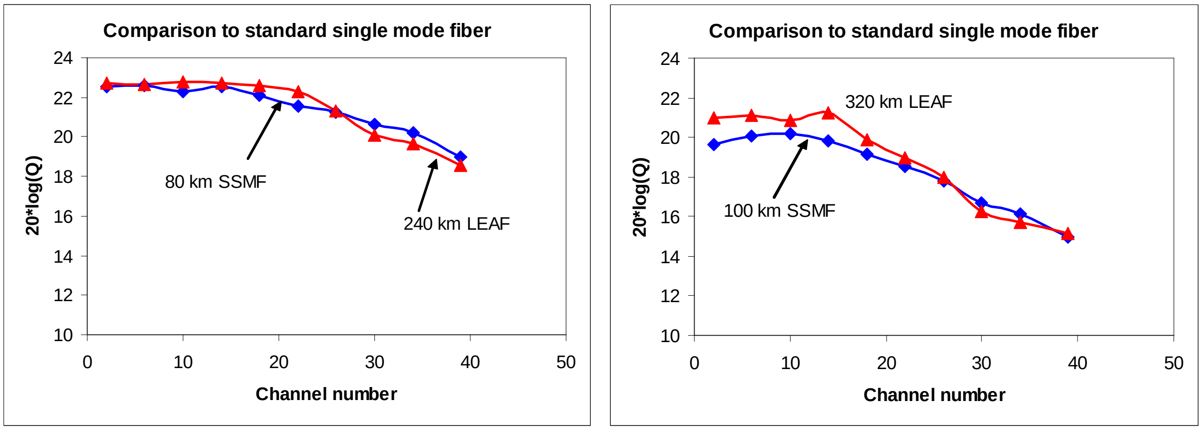
The experimental results show that uncompensated transmission through > 240 km is possible without FEC for all wavelengths in the C-band with BER values < $1\text{x}\ 10^{-15}$. Transmission over 320 km is easily achievable with the use of standard FEC, with a minimum margin of over 3.5 dB above the FEC threshold. Eye diagrams are shown in Figure 3 of the 1550.12 nm channel at 160, 240, and 320 km, demonstrating clearly open eyes at each distance.



(a) (b) (c)

Figure 3: Eye diagrams of channel at 1550 nm after (a) 160 km, (b) 240 km, and (c) 320 km of LEAF® fiber.

We next compared the DWDM performance of the 10 Gb/s NRZ signals modulated by the lithium niobate modulator as transmitted over the large effective area NZ-DSF and standard single mode fiber. Given that the transmission over the experimental system was primarily dispersion limited (the channel OSNR values even after 320 km transmission over LEAF® fiber were ~ 25 dB), we would expect that the attainable reach lengths will be roughly in inverse proportion to the dispersion values of the two fibers. To test the standard single mode fiber, we transmitted the 40 channel system over single span lengths of 80 km and 100 km. Some results that show the relative performance of the system over standard single mode fiber and over the large effective area NZ-DSF are shown in Figure 4. The results show that nearly equivalent transmission performance in terms of Q values over the C-band is achieved between the cases of 80 km of standard single mode fiber and 240 km of LEAF® fiber. Similarly, the performance over 320 km of LEAF® fiber is nearly identical to that of 100 km of standard single mode fiber. Thus, we can conservatively claim a factor of 3x or greater gain in optical reach with LEAF® fiber in comparison to standard single mode fiber at 10 Gb/s using this type of external modulator. Although not shown in Figure 4, significantly superior performance to that of standard single mode fiber at the same distances (80 or 100 km) is easily achieved with the lower dispersion LEAF® fiber.



(a) (b)

Figure 4: Comparison of 40 channel DWDM results over LEAF® fiber and standard single mode fiber. (a) 80 km of standard single mode fiber and 240 km of LEAF® fiber, (b) 100 km of standard single mode fiber and 320 km of LEAF® fiber.

3.2 Integrated electro-absorption modulated laser transmitters

Integrated electro-absorption modulated lasers (EMLs) form an important class of transmitter for metro and provincial networks because they offer good quality signal modulation at 10 Gb/s in a small package. In this type of transmitter, a distributed feedback laser (DFB) is monolithically integrated with an electro-absorption modulator on the same chip. Thus a single package contains both laser and modulator in a volume approximately the same size as a DFB laser alone. Since they are monolithically integrated, no alignment or connectorization is required between laser and modulator.

In our experiments here, we tested three discrete EML devices for transmission over both standard single mode fiber and the large effective area NZ-DSF. The experiment for transmission over LEAF® fiber was the same as is shown in Figure 1, except that in this case there were 39 lasers modulated by the lithium niobate modulator, and the EML under test was coupled with the other channels just after the external modulator. The wavelength of the EML under test occupied the empty 100 GHz channel created by the laser turned off in the original 40 lasers. Thus, there were still a total of 40 channels propagating in the system, with one of them being the EML under test and the other 39 being modulated by the lithium niobate device. The EMLs studied were all produced by the same manufacturer, and had wavelengths of 1534.25 nm, 1545.32 nm, and 1555.75 nm. The choice of these wavelengths enabled reasonably broad coverage of the C-band.

The results obtained with the 10 Gb/s EML transmitters were very similar to those found earlier with the lithium niobate external modulator. That is, 240 km transmission over LEAF® fiber was easily achieved with Q values above 18 dB (BER = 1×10^{-15}), even for the longest wavelength transmitter. Also, as before, transmission over 320 km was demonstrated with significant Q margin above the standard FEC threshold. These results are shown in Figure 5.

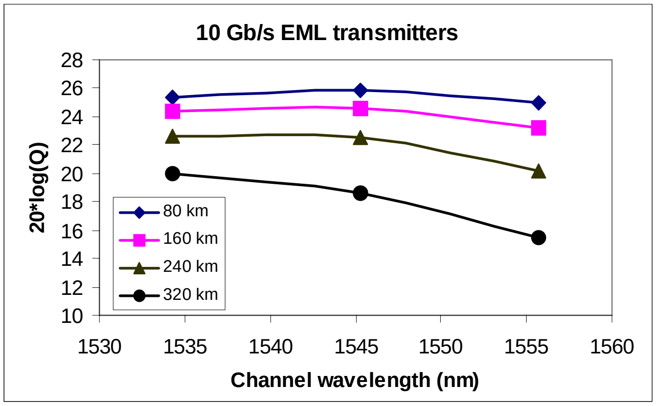
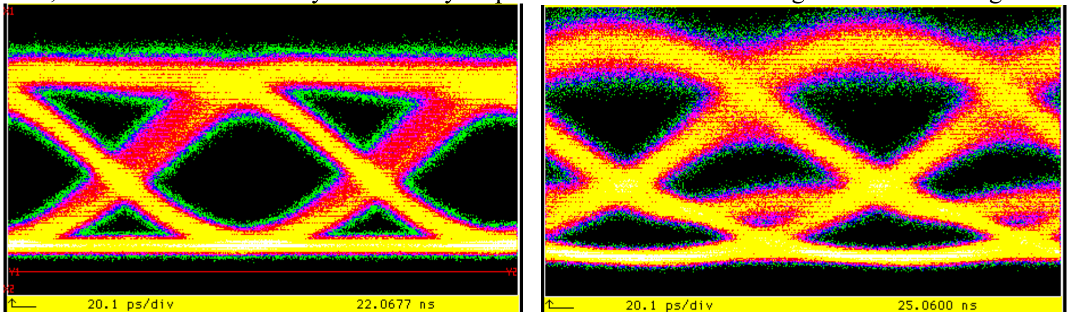


Figure 5: Results of signal Q values after transmission through up to 320 km of uncompensated LEAF® fiber with 10 Gb/s EML transmitters.

To compare the performance of the EML devices over LEAF® fiber and standard single mode fiber, we again measured the performance over single spans of 80 and 100 km of standard single mode fiber. For a visual qualitative comparison, consider Figure 6 which shows the eye diagrams for the EML at 1545 nm after 160 km transmission over LEAF® fiber and 100 km transmission over standard single mode fiber. It is clear that the eye is wide open after transmission over the LEAF® fiber, and much more severely distorted by dispersion from the shorter length of standard single mode fiber.



(a) (b)

Figure 6: 10 Gb/s eye diagrams of EML at 1545 nm after (a) 160 km transmission over LEAF® fiber, and (b) 100 km transmission over standard single mode fiber.

As with the external modulator, we found that the EML transmitters enjoyed a reach length with the large effective area NZ-DSF approximately 3 times as long as with standard single mode fiber, due to the relative dispersion levels of the fibers. This is supported by the data in Figure 7, which relates the signal Q values for the three EMLs over 240 km of LEAF® fiber and 80 km of standard single mode fiber. They are nearly identical.

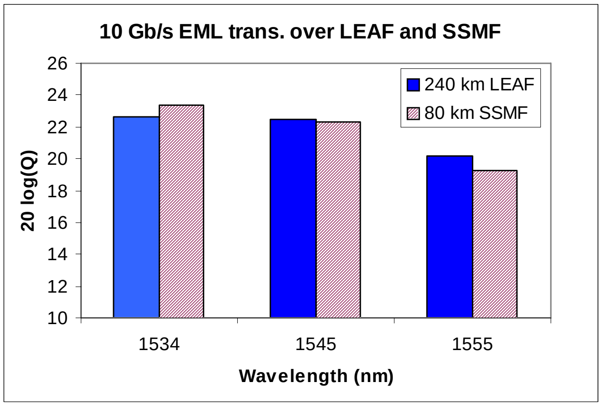


Figure 7: Q values of the three 10 Gb/s EMLs transmitted over 240 km of LEAF® fiber and 80 km of standard single mode fiber.

3.3 10 Gb/s directly modulated laser transmitters

The next category of transmitter potentially suited for moderate range metropolitan area network connections that was tested in this study was the 10 Gb/s directly modulated laser (DML). While nearly all 2.5 Gb/s transmitters used in metro/provincial networks are directly modulated, the use of directly modulated lasers at 10 Gb/s is fairly uncommon outside of the 1310 nm wavelength region. This is due to the severe dispersion limitations of the large positive chirp generally found with such transmitters, coupled with the high dispersion of standard single mode fiber (+17 ps/nm/km at 1550 nm). In fact, the reach over standard single mode fiber of this type of transmitter is usually on the order of only 15 km or so, which is not long enough for the majority of metro network links. However, the low dispersion of LEAF® fiber may make the use of inexpensive 10 Gb/s DMLs practical over metro link lengths found in many networks.

In our tests, we employed a set of 16 channels spaced by 100 GHz, at the blue end of the C-band. The wavelengths ranged from 1531 nm to 1542 nm. The 16 lasers were multiplexed together at the beginning of the link, although only one laser (the channel under test) was modulated with output from the pulse pattern generator at 10 Gb/s. It was not possible to modulate all lasers simultaneously due to the lack of a regenerating RF power splitter. However, no optical nonlinear impairments are expected over the fiber lengths of interest here at 100 GHz channel spacing[5], so the modulation of only the channel under test should be quite representative of a real WDM system using the 10 Gb/s DMLs. The first set of experiments with the lasers used a pre-amplified receiver. A 0.6 nm tunable filter was used for channel selection so as to be sufficiently wide to accommodate the signal bandwidth. The pseudo-random bit sequence used in the experiments was length 2^{31}-1. The extinction ratio of each transmitter under test was at least 8.0 dB, to conform to SONET standards. A schematic diagram of the experimental set-up is shown in Figure 8.

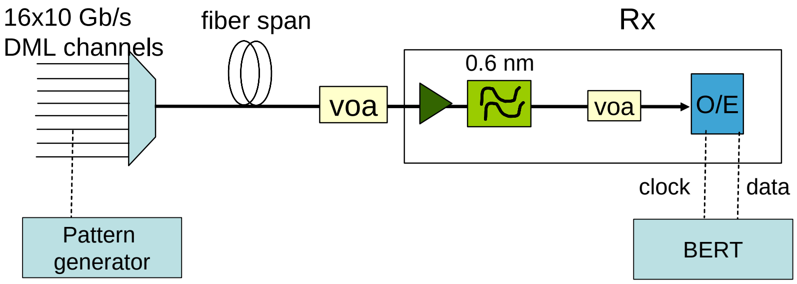
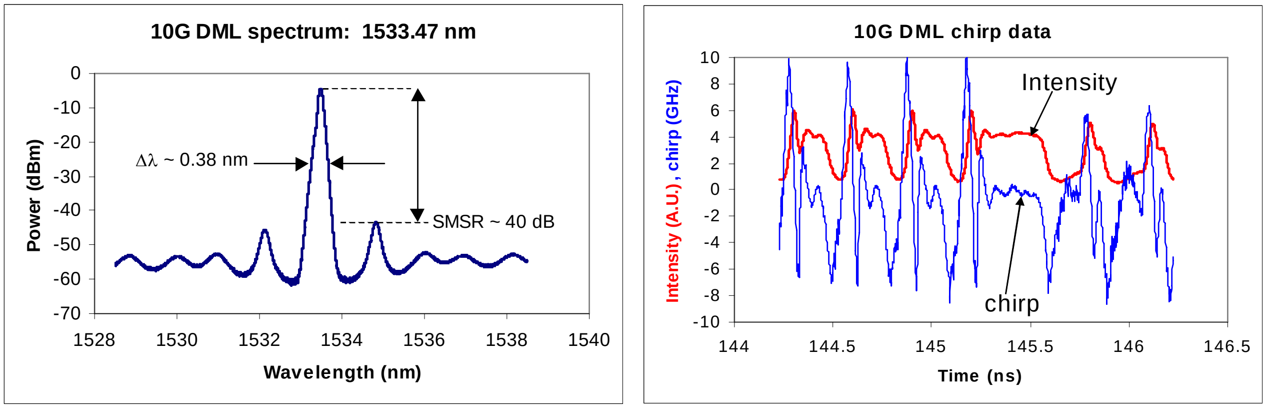


Figure 8: Experimental setup for 10 Gb/s DML transmission tests.

As mentioned above, the primary limitation of directly modulated 10 Gb/s transmitters is the high level of chirp. Examples of the modulated spectrum and the chirp waveform of one of the lasers tested are shown in Figure 9. The spectrum width is about 0.38 nm at the -20 dB level. The chirp waveform clearly shows a high degree of positive transient chirp, with frequency excursions up to approximately ±10 GHz. The linewidth enhancement factor (LEF) values for this laser and the others were measured to be generally in the range of +2.5 to +3.



(a) (b)

Figure 9: 10 Gb/s DML (a) spectrum, and (b) intensity and chirp waveforms.

The first experiments conducted with the 10 Gb/s DMLs addressed the attainable reach lengths over standard single mode fiber and the large effective area NZ-DSF. The channel at 1541.35 nm was transmitted over varying lengths of both fiber types and the Q values were measured. The results from this study are shown in Figure 10, where it is clear that there is a dramatic difference between the practical transmission distances achievable with each fiber. In particular, transmission over standard single mode fiber is limited to < 15 km with a Q value greater than 18 dB. On the other hand, the performance over LEAF® fiber with its lower dispersion is significantly better, and results for this wavelength indicate a reach of close to 80 km with a Q value over 18 dB. With easily achievable link connections over 50 km, the use of 10 Gb/s DMLs may become a very attractive option with LEAF® fiber in a metropolitan network.

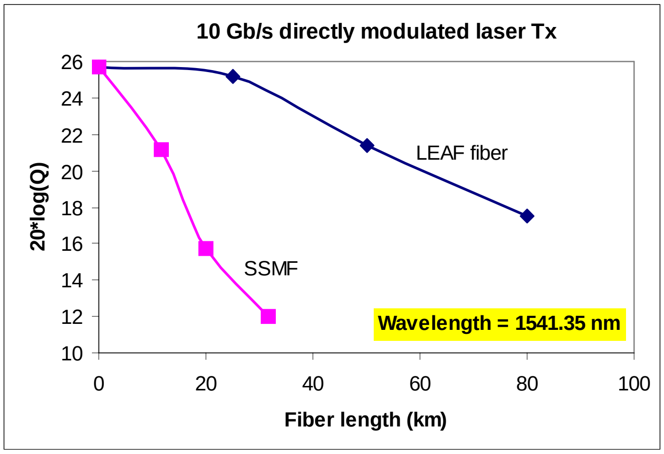


Figure 10: Performance of a 10 Gb/s DML channel as a function of fiber length over standard single mode fiber and LEAF® fiber.

We also measured the Q values for every second channel across the channel plan at distances of 50 and 80km, to demonstrate good performance across the available set of laser wavelengths. These Q results are presented in Figure 11, showing that all of the channels tested have Q values well above 21 dB at 50 km, and 17.5 dB or greater at 80 km.

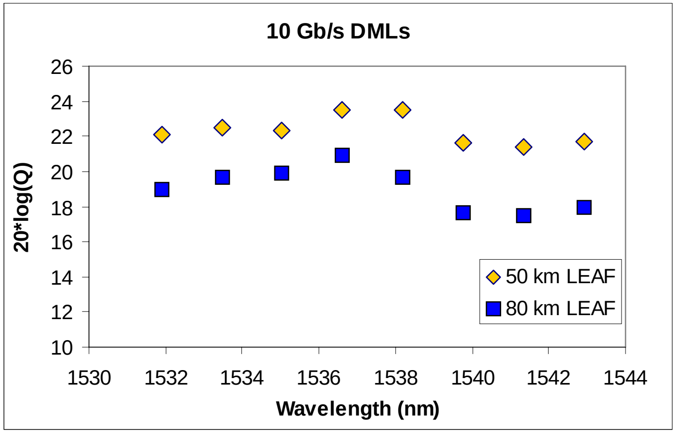


Figure 11: Q values of representative 10 Gb/s DML channels over LEAF® fiber.

An example of the power penalty for transmission through 50 km of LEAF® fiber is shown in Figure 12 for one of the 10 Gb/s DML channels. This data was obtained by transmission of the single channel through the fiber and 0.6 nm filter, and then into the optical-to-electrical converter. No pre-amplification was used to obtain the power-penalty results. The results show a power penalty of approximately 2.8 dB at a BER value of $1x10^{-10}$ for the 50 km of LEAF® fiber. The waterfall data through 20 km of standard single mode fiber is shown for comparison. The bend in the waterfall data for the standard single mode fiber is likely due to the fact that the dominant noise source shifts from thermal noise to shot noise at the higher power levels greater than -11 dBm.

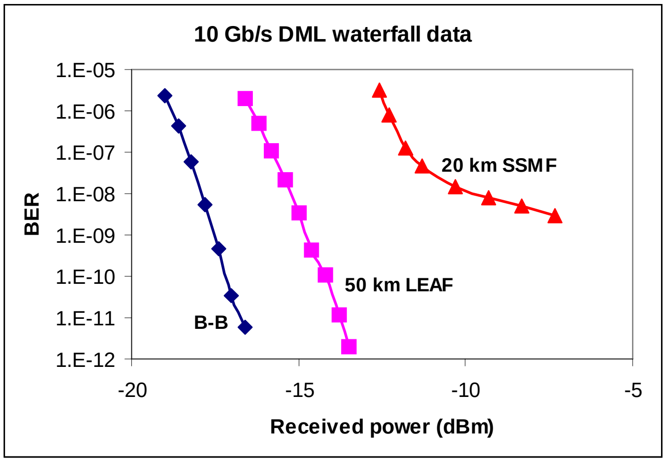


Figure 12: BER waterfall data of a typical 10 Gb/s DML channel over 50 km of LEAF® fiber and 20 km of standard single mode fiber.

3.4 2.5 Gb/s directly modulated laser transmitters

One of the most commonly used types of transmitters in metro and provincial networks is the 2.5 Gb/s directly modulated laser in the 1550 nm regime. Like 10 Gb/s DMLs, they often suffer from significant transient chirp that broaden their linewidth and limit their reach over standard single mode fiber[6]. However, since the dispersion tolerance at 2.5 Gb/s is a factor of 16 greater than at 10 Gb/s, these transmitters have found widespread use over standard single mode fiber, usually up to distances of 80-100 km. However, they are rarely used at longer distances because the dispersion-induced Q and power penalties become too great after 100 km. In fact, 2.5 Gb/s EMLs are increasingly being used to achieve longer distances over standard single mode fiber on the order of 300 km or more. In our experiments conducted here, we tested 2.5 Gb/s DMLs over 300 km of LEAF® fiber to demonstrate the significant extension in reach possible with this fiber using the less expensive and more commonly available directly modulated lasers. The NZ-DSF certainly also has better performance than standard single mode fiber over conventional distances of 100 km, but our objective here is to show that it can allow uncompensated transmission over a much longer link than could be achieved with standard single mode fiber.

The laboratory set-up used in the experiments is shown in Figure 13. A 32 channel DWDM system with 2.5 Gb/s DMLs in the C-band was transmitted over 300 km of LEAF® fiber, (and standard single mode fiber for comparison), in 3 spans of 100 km each. There were 16 channels at the blue end ranging from 1531.1 – 1542.9 nm, and another 16 channels at the red end from 1547.7 to 1558.9 nm. No dispersion compensation was used when testing either the large effective area NZ-DSF or standard single mode fiber. The average channel power into each span was 0 dBm. The DMLs tested were all typical 2.5 Gb/s transmitters from several different manufacturers that are rated for 100 km of standard single mode fiber, or approximately 1800 ps/nm of accumulated dispersion. To accurately capture any potential nonlinear penalties, all 32 channels were modulated during the measurements with a 2^{31}-1 length PRBS.

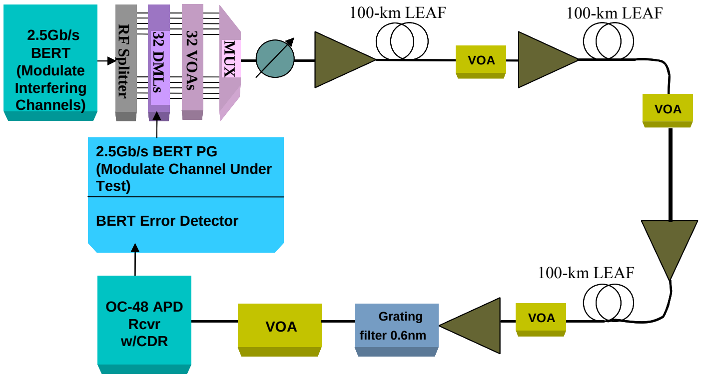


Figure 13: Experimental test set-up for 32 channel 2.5 Gb/s DML DWDM system over 300 km of LEAF® fiber.

The results for measured Q values through 300 km of both fiber types are presented in Figure 14. As mentioned earlier, the DML transmitters tested were rated for 100 km of standard single mode fiber, so one would not expect them to perform well over this longer distance of that fiber, but the data are given as a comparison to the performance over LEAF® fiber. The results in Figure 14 show that all 32 DWDM channels exhibit good transmission performance over the 300 km of LEAF® fiber, with all channels having a measured Q value greater than 18 dB, or corresponding BER values less than 1×10^{-15}. On the other hand, the performance over the same length of standard single mode fiber is poor, as expected, with a wide variation in performance between different lasers at different wavelengths.

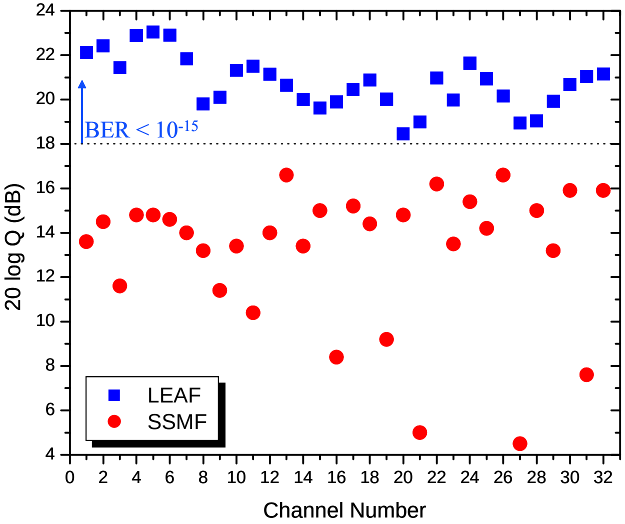


Figure 14: Measured Q value results for 32 channel 2.5 Gb/s DML DWDM system over 300 km of LEAF® fiber and standard single mode fiber.

No nonlinear impairments were observed in the transmission over the 300 km of LEAF® fiber. This was tested by turning off the 4 most adjacent channels and verifying that the Q factor of the channel under test did not change. The large effective area of the fiber is important in contributing to this lack of nonlinear penalty.

As an example of the quality of the signal transmission over 300 km of LEAF® fiber, consider the eye diagrams of the red-most channel (channel 32) in Figure 15, which show the eye in a back-to-back condition, and after transmission over the 300 km. The eye after transmission is clearly still wide open with little distortion from dispersion.

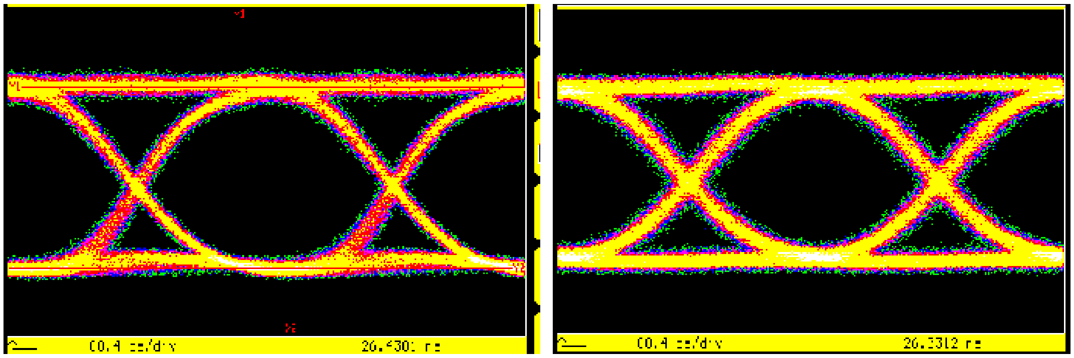

(a) (b)

Figure 15: Eye diagrams of channel 32: (a) in back-to-back condition, and (b) after transmission through 300 km of LEAF® fiber.

Another test of the transmission performance was measurement of the power penalty. This was done for 6 representative channels across the C-band through the 300 km of LEAF® fiber, and for all channels through 300 km of standard single mode fiber. The data in Figure 16 shows the power penalty data for the 6 channels through LEAF® fiber, and for 8 of the 32 channels through standard single mode fiber. The 8 channels whose data is shown through standard single mode fiber are the only channels with a power penalty < 10 dB. All other channels through standard single mode fiber had a power penalty much greater than 10 dB. The channels measured through 300 km of LEAF® fiber had a maximum power penalty of 2.1 dB. In both cases, the power penalty is measured against the case where the appropriate amount of attenuation was substituted for the fiber to achieve the same OSNR condition.

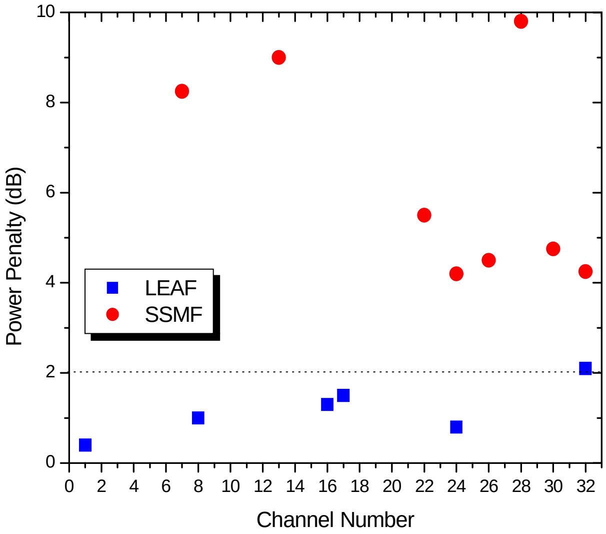


Figure 16: Measured power penalty of 2.5 Gb/s DMLs over 300 km of LEAF® fiber and standard single mode fiber.

3.5 CWDM system with 2.5 Gb/s directly modulated DFB lasers

The last set of experiments involved a coarse wavelength division multiplexing (CWDM) system with 2.5 Gb/s directly modulated DFB lasers. The system had 16 channels spaced by 20 nm, which spanned a 300 nm range from 1310 nm up to 1610 nm. The 16 channels were multiplexed together before transmission over the fiber under test, demultiplexed after the fiber span, and then a 1x16 optical switch selected one of the demultiplexed channels for submission to the receiver. Only the channel under test was modulated although all 16 channels were propagated. The receiver was an OC-48 APD with clock and data recovery. The optical system used in the experiment is shown schematically in Figure 17.

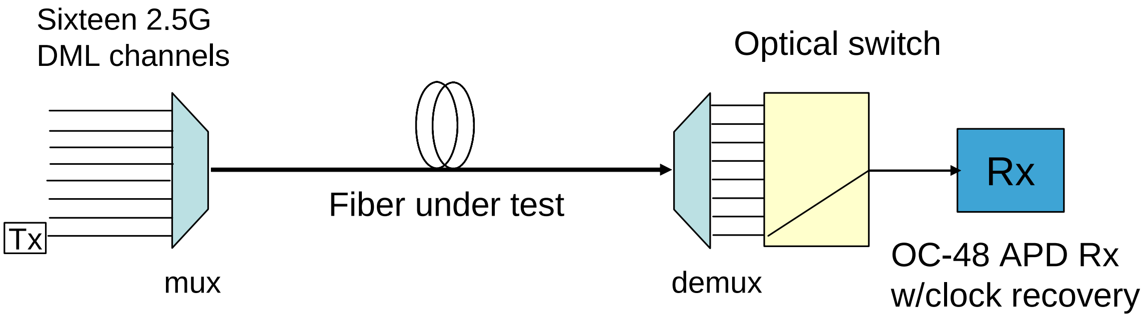


Figure 17: CWDM system experimental set-up.

Two spans of fiber were tested in this experiment: 50 km of LEAF® fiber, and 52 km of standard single mode fiber. The channel power levels launched into the fiber spans and leaving the fiber spans are shown in Figure 18. The power levels at the end of the spans do not include the demux or optical switch loss. The figure shows that this particular piece of standard single mode fiber has high water peak attenuation, leading to a significant power loss for the channel at 1390 nm. The large effective area NZ-DSF has a relatively low water peak in comparison, although the fiber was not deliberately selected for this characteristic.

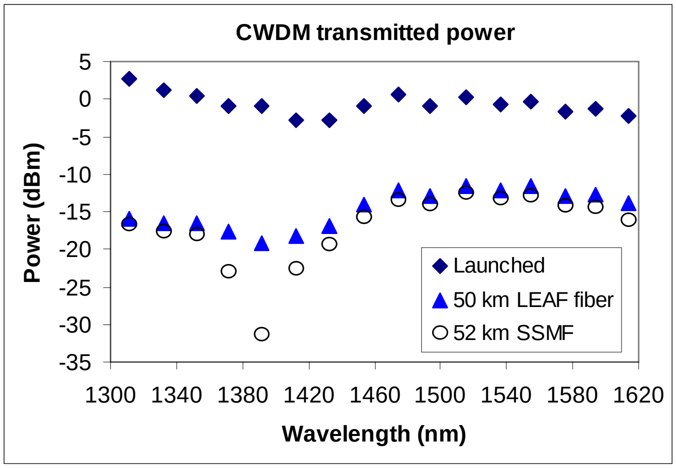


Figure 18: Channel power levels into, and out of, the fiber spans tested with the CWDM system.

The Q values were measured for the system in Figure 17 for both fiber spans. Fifteen out of the sixteen channels were measured, as the laser at 1470 nm was found to be defective and would not modulate correctly. The Q measurement results are shown in Figure 19. We see from these results that all channels transmitted through the LEAF® fiber have Q > 18 dB, corresponding to a BER < $1x10^{-15}$. The water peak channel at 1390 nm as transmitted through standard single mode fiber falls well below this threshold because of the excess attenuation. In addition to this, we can also see that the LEAF® fiber generally performs slightly better than the standard single mode fiber at all other wavelengths as well. This can probably be explained by the smaller penalty of the positive laser chirp values with lower positive dispersion of the large effective area NZ-DSF for wavelengths longer than 1500 nm, and slight pulse compression resulting from the negative dispersion of LEAF® fiber for wavelengths shorter than 1500 (compared to positive dispersion at these wavelengths for standard single mode fiber). Thus overall, LEAF® fiber appears to work well with positively chirped 2.5 Gb/s DFB lasers across the whole 300 nm CWDM band, and to have a slight advantage over standard single mode fiber in terms of dispersion properties.

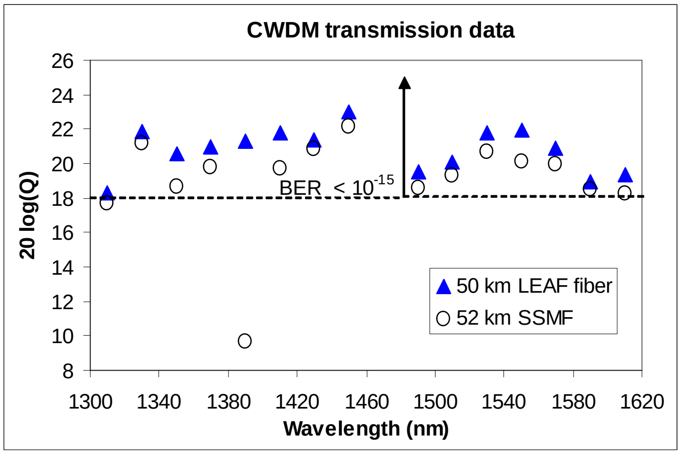


Figure 19: CWDM system Q results.

Finally, we also estimated the maximum reach length through LEAF® fiber for each CWDM channel based on the loss data and receiver sensitivity. We assumed sensitivity values of -24 dBm and -32 dBm for a PIN receiver, and an APD receiver, respectively. Assuming a 3 dB loss in the demultiplexer, and allowing another 2 dB for margin, we calculate the reach length data as shown in Figure 20. The estimates show the overall reach limited by the channel at 1390 nm, being about 50 km for a PIN receiver, and approximately 70 km for an APD receiver. We note that a standard single mode fiber with low water peak is expected to perform as well or better based on absorption limitations, and is likely to represent the overall optimal solution for a full spectrum CWDM system.

It should be noted that LEAF® fiber is not intended for use nor specified at 1310 nm. Corning recommends the use of ITU G.652.D compliant fibers, such as Corning's SMF-28e®, with emerging CWDM technologies. LEAF® optical fiber is optimized for performance in the 1550nm window.

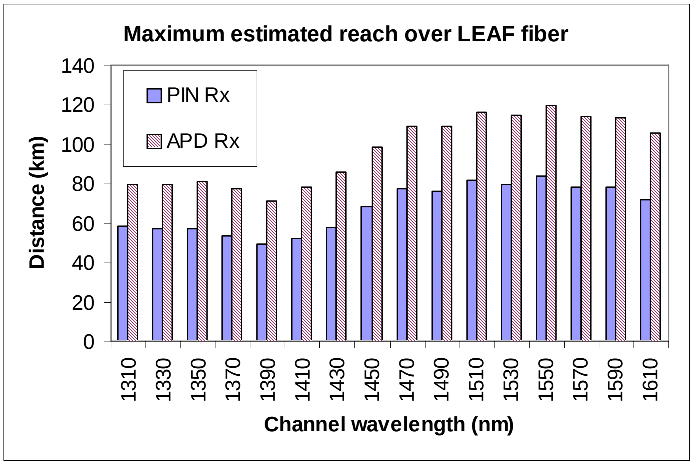


Figure 20: Estimated maximum reach length over LEAF® fiber based on loss and receiver sensitivity.

4. SUMMARY

We have performed a series of experiments testing the uncompensated transmission performance of LEAF® fiber with metropolitan and provincial network transmitters, and compared the results obtained to those using standard single mode fiber as the transmission medium. We found that the uncompensated optical reach is extended by a factor of 3-4 for many sources in the C-band such as 10 Gb/s external modulators, 10 Gb/s EMLs, 10 Gb/s DMLs, and 2.5 Gb/s DMLs. In addition, a 16 channel CWDM system with 2.5 Gb/s DFB lasers was tested and all channels over the 300 nm range had Q values > 18 dB for transmission over 50 km of LEAF® fiber. Aside from a high water peak of the particular span of standard single mode fiber tested, the performance of the CWDM system was slightly better for LEAF® fiber than for standard single mode fiber because its dispersion characteristics over the full 300 nm range are advantaged with the positively chirped directly modulated 2.5 Gb/s transmitters.

These results indicate that a large effective area non-zero dispersion shifted fiber such as LEAF® fiber may be well-suited for many metro/provincial networks. It not only works well with the 1550 nm 2.5 Gb/s DFB lasers widely deployed today, but it extends their range to include longer metro links and possibly transmission from one metro network to another within a provincial network area. It also guarantees exceptional performance in the future with higher bit rates such as 10 Gb/s, also extending the reach of most externally modulated lasers and EMLs to approximately 300 km or more. It may also make the use of 10 Gb/s DMLs practical and cost-effective in the 1550 nm wavelength region, since it offers realistic transmission distances with these sources of 50-80 km, compared to 15 km or less over standard single mode fiber. Overall, our results suggest that hybrid cable designs containing large effective area NZ-DSF LEAF® fiber and low water peak standard single mode fiber may well satisfy metropolitan and provincial transmission requirements, offering optimized performance and flexibility in network designs.

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